DUAL FREQUENCY ANTENNAS AND ASSOCIATED DOWN-CONVERSION METHOD

FIELD OF THE INVENTION

The present invention relates to microwave, millimeter and submillimeter wave and optical antennas, and more particularly, to a dual frequency antenna and associated method for converting electromagnetic radiation from a first and second frequency to a third, a difference frequency and reradiating the resulting difference frequency.

BACKGROUND OF THE INVENTION

As described in co-pending U.S. Patent application 10/444,510 incorporated herein by reference, Figure 1 illustrates two sources of electromagnetic radiation **10, 20** radiating collimated beams **12, 22** of electromagnetic radiation at two separate frequencies, f_1 and f_2, and in two intersecting directions that produce interference at a distance. Generally, when two electromagnetic beams of different frequencies converge, the volume of the intersection **24** will include a frequency component which is equal to the difference in frequency of the two beams, which is defined herein as the interference difference frequency, Δf. More specifically, the electromagnetic interference at the interference difference frequency, Δf, is optimal in that the electromagnetic interference field strength is at a maximum when the beams are diffraction limited and collimated having substantially equal intensities and either linearly or circularly polarized. When the interference difference frequency is incident upon electronic components at or near the interference frequency, the resultant field will interfere with the operation of the electronics.

The interference difference frequency, Δf, is generated by intermodulation, which is defined as the production in an electrical device of currents having frequencies equal to the sums and differences of frequencies supplied to the device. In this regard, intermodulation occurs through nonlinear surface and volume effects (such as oxide layers, corroded surfaces, etc.), also by nonlinear electronic circuit parts and components, such as diodes, transistors, which are parts of all integrated circuits, receiver front-ends, and other circuit parts that may resonate with either or both the main and difference frequencies that are projected. For example, when the collimated and coherent outputs of two distinct millimeter wave sources are 100 GHz

and 101 GHz, the electromagnetic field at the intersection **24** will include a 1 GHz component. Physically, the interference pattern created in the volume of the intersection of collimated parallel polarized beams is a fringe field where the fringe planes are parallel to one another. The fringe planes are traveling in a direction perpendicular to the planes at the rate of the interference difference frequency, *i.e.* difference between the frequencies. The fringe planes are separated by the fringe period, Δf, which is determined by

$$\lambda_f = \frac{\lambda_o}{2\sin\frac{\theta}{2}} \qquad (1)$$

where λ_o is the average wavelength of the two collimated beams, and θ is the angle of intersection between the two collimated beams. As can be seen, the fringe period depends upon the angle of intersection of the intersecting beams. Additionally, when the beams are at substantially equivalent field strengths, full amplitude modulation of the interference field will be achieved.

Figure 2 illustrates an alternate method to converge electromagnetic beams at a distance in a special case of the converging angle $\theta = 0$. Two electromagnetic radiation sources **30, 40** radiate collimated beams **32, 42** of electromagnetic radiation at two separate frequencies, f_1 and f_2, and in the direction of a polarization beam combiner. The polarization beam combiner combines orthogonally polarized beams by reflecting one beam and permitting transmission therethrough of the other beam. The resultant output is therefore the combined beams of both collimated beams **32, 42** having an interference difference frequency as described above. Again, for example, if f_1 = 100 GHz and f_2 = 101 GHz, the resultant interference difference frequency Δf = 1 GHz. In contrast to the above description, however, the intersection angle, θ, between the two beams is reduced to zero. As such, the fringe period has become infinite, that is to say that there are now no fringes and no spatial variation of intensity in any plane perpendicular to the direction of beam propagation.

In a typical arrangement, the polarization beam combiner **34** is oriented at 45 degrees with respect to the beams (**32, 42** in Figure 2). The polarization beam combiner **34** is rotated to transmit the linearly polarized incident beam **42** with the minimum of loss. The other beam (**32** in Figure 2) will be polarized orthogonal to the first beam to obtain maximum reflection and minimum transmission loss through the polarizer. Once these two beams are combined, they are superimposed and may be

directed. That is to say that both beams **32**, **42** are transmitted within one effective beam rather than separate converging beams (as described in Figure 1), and the resultant interference zone **44** is the volume occupied by the merged beams, from the polarizer and beyond.

While a linear polarization beam combiner **34** has been discussed above other embodiments of beam combiners, known to those of ordinary skill in the art, including beam splitters, circular polarization beam combiners, and the like may be substituted accordingly. Additional information relating to superimposition of electromagnetic beams is further described in the background, above, and in co-pending U.S. patent application 10/444,510 incorporated herein by reference.

Having developed methods of effectively combining electromagnetic beams at distant locations, it would be desirable to utilize the difference frequency generated in these interactions. In particular, due to efficiencies of better diffraction limited beams at higher, optical frequencies, it would be useful to down-convert higher frequencies for re-radiation of the lower frequencies.

As used herein, several terms should first be defined. By definition, microwaves are the radiation that lie in the centimeter wavelength range of the EM spectrum (in other words: $1 < \lambda < 100$ cm, that is, the frequency of radiation in the range between 300 MHz and 30 GHz, also known as microwave frequencies). Electromagnetic radiation having a wavelength longer then 1 meter (or frequencies lower then 300 MHz) will be called "Radio Waves" or just "Radio Frequency" (RF). For simplicity in this disclosure, the RF spectrum is considered to cover all frequencies between DC (0 Hz) and 300 MHz. Millimeter Waves (MMW) are the radiation that lie in the range of frequencies from 30 GHz to 300 GHz, where the radiation's wavelength is less than 10 millimeters. Finally, electromagnetic frequencies from 300 GHz to 30 THz are described as submillimeter waves, or terahertz frequencies. Anything above 30 THz are considered as optical frequencies (or wavelengths), which includes infrared (IR) and visible wavelengths. The optical range is divided into bands such as infrared, visible, ultraviolet. For purposes of this disclosure, millimeter and submillimter frequencies are described throughout, however, these same principles apply to submillimeter and smaller (higher frequency wavelengths), therefore submillimeter, as used herein, can include optical frequencies. As known to those of ordinary skill in the art, for practical purposes the "borders" for

these above these frequency ranges are often not precisely observed. For example, a cell phone antenna and its circuitry, operating in the 2.5+ GHz range is associated with RF terminology and considered as part of RF engineering. A waveguide component for example, covering the Ka band at a frequency around 35 GHz is usually called a microwave (and not a MMW) component, etc. Accordingly, these terms are used for purposes of consistently describing the invention, but it will be understood to one of ordinary skill in the art that alternative nomenclatures may be used in more or less consistent manners.

BRIEF SUMMARY OF THE INVENTION

According to one embodiment of the invention, a dual frequency antenna comprises a plurality of dipole antennas configured to receive first and second frequencies. The antennas are arrayed to an effective length to reradiate at a third frequency, which is down-converted from the first and second frequencies. A plurality of nonlinear resonant circuits interconnect the plurality of dipole antennas and are configured to permit reradiation of the second frequency over the effective length. According to one aspect of the invention the plurality of dipole antennas comprise half wavelength dipole antennas. According to another aspect of the invention, the plurality of dipole antenna may comprise electric dipoles.

The nonlinear resonant circuits that interconnect the plurality of dipole antennas typically include both capacitive and inductive circuit elements and a nonlinear element. The reactive circuit elements are resonant at the resonant frequency of the dipoles. The reactive elements typically comprise combinations of capacitive and inductive circuit elements. The resonant circuit also need to include a nonlinear circuit element, such as a diode. The nonlinear element permits the down-conversion of the first and second frequencies to their difference frequency, a beat frequency.

According to another embodiment of the invention, a method of down-converting at least first and second electromagnetic radiation frequencies is provided. The method includes transmitting a first electromagnetic beam at a first frequency and transmitting a second electromagnetic beam at a second frequency offset from the first frequency by a difference frequency. The first and second electromagnetic beams are received by at least two dipole antennas. The first and second frequencies are down-converted to the difference frequency through nonlinear resonant circuits coupling

multiple dipole antennas. The coupling of the dipole antennas permits transmitting the difference frequency.

One aspect of the method includes transmitting the first and second electromagnetic beams in intersecting directions. As such, the reception of the first and second electromagnetic beams is performed in the intersection area. Alternatively, the first and second electromagnetic beams may be combined and transmitted in the same direction. For example, they may be combined through a polarization beam combiner.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

Figure 1 is a prior art schematic representing the effects of combining two coherent collimated electromagnetic beams with two different frequencies;

Figure 2 is a prior art schematic representing the effects of combining two coherent collimated electromagnetic waves with a polarization beam combiner;

Figure 3 is a plan view of a plurality of dipole antennas interconnected by nonlinear resonant circuits according to one embodiment of the present invention; and

Figures 4(a) and (b) are schematic diagrams showing details of a simple nonlinear resonant circuit connecting to the tips of two consecutive dipole antennas according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present inventions now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the inventions are shown. Indeed, these inventions may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

Electromagnetic radiation in the RF (radio frequency), microwave, millimeter and optical wave ranges interacts with thin conducting bodies, such as wires when the conductor is aligned with the electric field of radiation. The interaction is dependent upon conductor length, l, in relation to the radiation wavelength, λ. A half

wavelength dipole antenna, for example, will resonate and reradiate for a conductor length that is one half the radiation wavelength. For any such antenna, the antenna converts the electromagnetic wave to an induced voltage and current. As described above, converged or intersecting beams of electromagnetic radiation at two different frequencies, f_1 and f_2, exhibit a difference frequency, Δf, component that can be physically reproduced by intermodulation through nonlinear circuit elements. The intermodulation function of the diode converts the two frequencies to their beat frequencies, one of which is the difference frequency. Conductors and nonlinear circuit elements placed in this intersection of beams can be employed to reradiate the difference frequency. If resonant elements are incorporated in a nonlinear circuit, the circuit can be tuned to selectively resonate the difference frequency.

Referring to Figure 3 and one embodiment of the invention, a dual frequency nonlinear antenna **50** can reradiate electromagnetic radiation to the difference frequency by employing a nonlinear resonant circuit (NRC) **54** interconnecting multiple antennas **52**. The nonlinear resonant circuit **54** is frequency selective, mixing frequencies to the desired resonant frequencies between each antenna **52**. In this embodiment, a dual frequency nonlinear antenna **50** comprises a plurality of dipole antennas **52** interconnected by nonlinear resonant circuits **54** that couple frequencies of the antennas. The dual frequency nonlinear antenna **50** can convert the interfering pattern of two beams with frequencies, f_1 and f_2. The electrical length, l_d, of each dipole antenna **52** is approximately half the wavelength of each electromagnetic wave beam, $\lambda_o/2$ (the interfering two beams are near enough in wavelength that the antenna adequately receives both frequencies). The total electrical length, l_t, of the dual frequency nonlinear antenna **50** is one half the wavelength of the difference frequency, $\lambda_\Delta/2$.

To down-convert the first and second frequencies, the dual frequency nonlinear antenna **50** is aligned with the direction of the electric field of the first frequency beam and a second frequency beam (see Figures 1 and 2), which are separated by a difference frequency. Frequencies of each of the first and second beams are relatively close to one another such that the resonance of each individual half wavelength dipole antenna **52** is an effective receiving antenna at both frequencies. The nonlinear resonant circuit **54** is tuned to be resonant at a frequency, halfway between the frequencies of the two beams so as to permit the interconnection of the individual dipole antennas at the difference frequency but appear as an open

circuit at the first and second frequencies. A nonlinear element, such as a diode (not shown), facilitates generation of the difference frequency. Therefore, by providing the identical frequency selective circuits that connect the adjacent dipoles, it will make the multiple antennas radiate together at the difference frequency, while allowing the individual dipoles between the resonant circuits to resonate at the two individual beam frequencies.

In this regard, the first and second frequencies are effectively down-converted to the difference frequency for reradiation by the total effective length of the dual frequency antenna **50**. The total effective length of the antennas, therefore, also is approximately half the wavelength of the difference frequency if the dual frequency antenna structure is in vacuum (or air), and effectively a half dipole antenna at the difference frequency such that the antenna reradiates the difference frequency if the dual frequency dipole structure is in a dielectric medium, or mounted on a dielectric plate (such as glass, sapphire, silicon) the mechanical length of the structure must be shortened in order to maintain the electrical length at $\lambda_\Delta/2$. The reradiated frequency may be employed in a number of ways, such as employing coupling mechanisms, directors, or reflectors.

An example more fully illustrates this embodiment in Figure 3. A 10 GHz incident electromagnetic radiation interference pattern may be produced by two collimated electromagnetic beams, one beam having a frequency of $f_1 = 95$ GHz ($\lambda_o \approx$ 3 mm), and the other beam having a frequency of $f_2 = 105$ GHz ($\lambda_o \approx 3$ mm). The resultant interference difference frequency is then 10 GHz ($\lambda_\Delta \approx 3$ cm). In this embodiment, eight dipole antennas **52** are chosen, each dipole antenna is approximately one half of the millimeter wave electromagnetic radiation wavelength that is an electrical length of $l_d = 1.5$ mm. Each dipole antenna **52** is disposed in the same direction as the other dipole antennas having a spacing of about 430 microns such that the total effective electrical length, l_t, of all dipole antennas is 15 mm, which is approximately half of the difference frequency wavelength. It will be noted that other numbers of dipole antennas could be used and spaced to obtain a total effective length of approximately one half the interference frequency wavelength. For example, nine dipole antennas could be employed instead of 8, and a resultant spacing of 200 microns therebetween would also yield a total effective length of 15 mm. It will be noted by those of ordinary skill that mechanical and electrical lengths are almost the same in air, but are different in relation to materials depending upon the

dielectric properties of surrounding materials. When a dipole is mounted on a dielectric plate (hemispace with a dielectric constant ε), the mechanical length of a dipole must be shortened to maintain the resonance condition, i.e. to maintain that the electrical length stays $\lambda/2$.

Referring to Figure 4(a), as each dipole antenna **52a** is joined by a nonlinear resonant circuit **54a** comprised of reactive elements, in this embodiment an inductor, **L**, and a capacitor, **C**, and a nonlinear element, in this embodiment a diode, **D**. The reactive components are configured to provide an effective open circuit to beam frequencies, f_1 and f_2, and a quasi short circuit at the lower (difference) frequency, Δf. The diode is the nonlinear circuit element that promotes the intermodulation of the two frequencies to their beat frequencies. It will be understood by those of ordinary skill in the art that other resonant circuits or filtering circuits or alternative nonlinear circuit elements may be employed in various forms other than these listed, and are well known in the field of electromagnetic signal processing.

In one embodiment illustrated in plan view of Figure 4(b), a nonlinear resonant circuit **54b** may comprise a conductive planar loop **56** and p-n junction **58** or a Schottky diode deposited on a substrate with a layer of insulation, such as a substrate of silicon with an oxide layer on top ($Si0_2$) by using lithographic manufacturing techniques. In order to obtain the resonant qualities of an antenna as described in the example above, the capacitance and inductance would be quite small. Depending upon the resonance frequency desired, a small one turn conductive planar loop **56** (or just a fraction of a loop) is all that is needed in order to facilitate fabrication of a high frequency, resonant circuit using standard monolithic deposition techniques. As an example at extremely high frequencies, a capacitive values of one femtoFarad is typical to obtain resonance at 30 THz frequency (wavelength is 10 micron). Conductive material, such as aluminum or other conductive materials, is looped to form an inductive element, **L**, while opposite ends of the loop are overlaid with an insulator therebetween, such as aluminum oxide, to form a parallel plate capacitive element **C**. In this regard, the inductive and capacitive properties are controlled by the dimensions of the loop and the oxide layer thickness in order to obtain the appropriate values of inductance and capacitance. The diode **58** may be formed in a number of different ways, such as creating a metal-oxide-metal (MOM) sandwich, which forms a tunneling junction diode (such as Nickel-NiO-Nickel) if the oxide layer thickness is kept 50A or less (and that thickness is carefully controlled).

Schottky planar diodes or the Schottky "cat-whisker" type diodes for very high THz frequencies is an example of other types of diodes like linearly adjacent regions formed of p and n material in accordance with monolithic manufacturing techniques. Likewise, the dipole antennas **52b** may also be disposed and comprised of materials such as aluminum, gold, silver, cooper, nickel etc. to facilitate deposition in combination with the planar conductive loop **56**.

The foregoing is illustrative of one embodiment of a dual frequency dipole antenna comprising half wavelength electric dipole antennas effectively arrayed to achieve a dual frequency half wavelength electric dipole antenna. It will be understood by one of ordinary skill in the art that a dual frequency antenna may comprise other forms of dipole antennas. For example, a magnetic dipole antenna (conductive loop) exhibits fields corresponding to those of an electric dipole antenna with reversed electric and magnetic fields. Therefore the properties and effects of a series of a plurality of magnetic dipole antennas interconnected by nonlinear resonant couplers in a manner similar to the above would be apparent to one of ordinary skill.

The dual frequency antenna may be provided in an arrayed plurality of dual frequency antennas separated by the distance between fringe peaks. As discussed above, the fringe fields are separated by a distance that can be determined using equation (1) and are normal to the difference frequency traveling wave. To reradiate the difference frequency at maximum amplitudes, the dual frequency antenna may be arranged in rows separated by the distance between fringe peaks.

Alternatively, when the first and second electromagnetic beams are combined with a polarization combiner prior to down-converting there are no fringes or spatial variation of intensity in the plane perpendicular to the direction of beam propagation. Combined beams permit arranging the dual frequency antennas to reradiate in phase when separated by a distance equivalent to the fringe field peaks. The in phase reradiation of the down-converted frequency, therefore, produces a phased array of antennas. By arranging the array in rows 2N+1 dual frequency antennas, the lobes of the antennas effectively cancel and promote a diffraction limited radiation pattern from the array.

Many modifications and other embodiments of the inventions set forth herein will come to mind to one skilled in the art to which these inventions pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the inventions are not to be limited to

the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.